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RESEARCH MEMORANDUM

A STUDY OF MEANS FOR RATIONALIZING AIRPLANE DESIGN LOADS

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

Results are presented from a study of means for rationalizing the design loads of airplanes based on mission requirements. It is indicated that the load experience may be broken down into specific mission operations and nonmission operations. A tentative standard probability curve for nonmission operations is presented, and the possibilities of calculating the load experience in missions are indicated. The two types of curves are then combined to form the resultant load-history curve for the airplane.

INTRODUCTION

The NACA has been making a study of means for rationalizing the design loads of airplanes based on mission requirements. The study, which utilizes statistical methods, is in its initial stages but it is believed that some of the preliminary ideas may be of some interest at this time.

This study has been based on the premise that an airplane should be designed for the mission or missions for which it is to be used. Conceivably, in the future it may be desirable to design for more specific missions which will be governed by the range of the detection apparatus, the armament, and the type of directing devices. It may then be found necessary to do something a little different from in the past.

Of course, all statistical measurements which are used must, of necessity, be based on operational airplanes which by some standards are obsolete when they become operational. The airplanes for which statistical data are now available are all subsonic or low-supersonic airplanes which are reasonably stable airplanes. The results for airplanes with serious stability deficiencies could be considerably different if they were flown operationally with such stability deficiencies. In the following discussion, therefore, it will be assumed that the stability deficiencies will have been corrected or the airplanes restricted such that they will be able to perform their design mission without encountering any uncontrollable motions.

[redacted]

SYMBOLS

M	Mach number
n	load factor
n_L	service limit load factor
t	flight time (on the average) to exceed given value of n
t_i	time to exceed given value of n in particular operation
t_0	time to exceed $n = 1$ in maneuvers, $\frac{1}{N_0/T}$
N_0/T	average number of major load-factor peaks per hour of flight time
T	total flight time
T_i	flight time spent in particular operation
σ	root-mean-square value of load-factor ratio $(n - 1)\big/(n_L - 1)$

DISCUSSION

Airplane Uses

Table I lists some of the missions and operations for which a fighter-type airplane might be used. In the group above the double line are the missions for which the airplane might be designed, and in the group below the double line are other operations for which the airplane will be used but which may be of secondary importance to the missions. Several missions or uses are indicated in the first two columns, and of course there are other missions that could be added to the list. In the third column are listed percentages of the total flight time which might be spent in each activity. For each of these uses of the airplane, there would be an associated probability function such as shown in the fourth column. In this column, probability functions for the airplane uses are indicated as average flight time required to exceed a given load factor. The probability curves for the part of the table above the double line are dictated by the mission requirements, whereas the probability curves for the lower part of the table or nonmission operations appear to depend mostly on the pilot's ability to observe a placard load-factor restriction. These component curves are then combined according to the percentage of flight time spent in missions or in other operations to obtain a resultant probability curve.

Probability Curves for Specific Mission

It appears that the probability curves for the individual missions may be calculated in some cases. The first work of this type was done by Brönn of the SAAB of Sweden. In figure 1 a simple mission is indicated for which probability curves have been calculated. In this case, it is assumed that a Mach number 2 piloted interceptor is to intercept a Mach number 1 bomber which is approaching the target at an altitude of 60,000 feet. The bomber is detected by ground radar stations. Probability curves are then calculated or estimated for the various phases of the mission such as the take-off, climb, cruise, turn on to the target, attack, breakaway, and landing. The possibilities of a miss on the first attack and subsequent attacks are also included in the calculations although not indicated in this figure. The turn on to the target is assumed to be directed from the ground control stations. The probability function for this turn is related to the ability and probability of the ground radar installation to direct the interceptor to the optimum position for attack.

The method of calculating the probability functions for a simplified version of the attack phase of the mission is indicated in figure 2. At the beginning of the attack phase the interceptor is at the position shown in the figure. The lines denoting various loads (or load factors) represent possible locations of the bomber at the beginning of the attack. For example, if the bomber were located anywhere along the line labeled 2g at the beginning of the attack, the interceptor would have to make at least a 2g turn for a successful interception; if the bomber were located anywhere along the line labeled 4g, the interceptor would have to make at least a 4g turn, and so forth. The dashed-line circle represents the interceptor's initial airborne radar range, which in this case was assumed to be 20 miles. The concentric solid-line circles are lines of constant probability which are a function of the ability of the ground control to position the interceptor in the optimum location for a successful attack. For example, the bomber will be located within the area enclosed by the circle labeled 10% in 10 percent of the cases, the bomber will be located within the area enclosed by the circle labeled 50% in 50 percent of the cases, and so forth. The probability of the interceptor exceeding a given load factor is then determined by the volume of the probability distribution falling outside of a given load-factor line. Of course, this is a simplified version of the attack phase of the mission, but it is presented in order to illustrate the use of the mission concept to determine the loads which might be imposed. It is not intended to be an actual interception problem.

The probability curve obtained in this manner is shown in figure 3. The probability curve for the attack phase is shown as the average flight time required to exceed a given load factor. The probability curves for the other phases of the mission are also calculated or estimated. A few of these are shown, such as the take-off, turn on to target, and the gust expectancy. These individual probability curves are then combined to form the total mission probability curve which is shown as the heavy line.

Probability Curves for Nonmission Uses

For the other uses of the airplane such as shown in the lower part of table I, it has been indicated from experience with present-day airplanes that the maneuver load experience other than the specialized mission may be approximated by one probability function which is proportional to the airplane service limit load factor. (See refs. 1 and 2.) This is shown in figure 4.

In figure 4, the ratio of the time to exceed a given load factor to the time to exceed 1 g in maneuvers is shown plotted against the ratio of incremental load factor to incremental service limit load factor. The time to exceed 1 g in maneuvers, t_O, is determined by plotting t against $\left[(n - 1)/(n_L - 1)\right]^2$ and extrapolating linearly back to zero. The data shown represent about 20,000 hours of total flight time in training and combat. It may be seen that, although there is considerable scatter, the data may be represented by one line and the curve shown appears to fit the data for airplanes with limit load factors as low as 2.8 and as high as 7.5 at load factors up to the service limit load factor.

It is indicated that this tentative standard curve may be represented by an equation of the type shown in figure 4. It can be shown from statistical theory that such an equation represents the distribution of the larger peak load factors if it could be assumed that the maneuvering load factors were of a random nature and symmetrical about 1 g. It may be noted that the load-distribution curve is determined only by the term N_O/T and the term σ; N_O/T represents the average number of major load-factor peaks per hour and σ represents the root-mean-square value of the load-factor ratio. For present operational U. S. Air Force fighters in training and in combat, the value of N_O/T varies between 10 and 25 peaks per hour and the value of σ is about 0.284. Of course, individual maneuvers are not of a random nature; however, when many maneuvers are considered together it appears that they may approach the concept of a random process.

Selection of Limit Load Factor

If, now, it is assumed that the mission probability curve can be calculated and that the probability curve for other airplane operations can be given as shown in figure 4, the two types of probability curves may be combined to form the resultant curve. If it is assumed, for example, that the airplane will spend 20 percent of its flight time in the specialized high-altitude interception mission described previously and 80 percent of its flight time in other operational uses, the limit load factor could be selected in the manner indicated in figure 5.

On the left side of figure 5 is shown the probability curve for the specialized high-altitude interception mission in terms of flight time required to exceed a given load factor. On the upper right side of figure 5, the standard maneuver curve for the other operational uses is shown as a function of limit load factor. The curve shown is given for an assumed value of the average number of load-factor peaks per hour which may be estimated on the basis of past experience.

By assigning various values of the limit load factor to the upper curve, a series of probability curves are obtained as shown at the bottom on the right side of figure 5. At this point the limit load factor to select is not known; however, it is known that the airplane with the longest life at the least expense in weight is wanted. Therefore, if the mission curve is combined with each of the curves representing different limit load factors on the basis of 20 percent of the flight time spent performing the mission and 80 percent spent in nonmission operations, a series of resultant probability curves, one for each limit load selected, would be obtained. The flight time required to exceed the limit load factor for each of the resultant curves would vary for the different cases.

In figure 6 the standard (or nonmission) curve based on limit load factor has been combined with the mission curve in the manner indicated above. Each bar represents an airplane having a given limit load factor and capable of performing the high-altitude interception mission previously mentioned. The height of each bar represents the flight time required to exceed the particular limit load factor for each case. For example, the height of the bar labeled 2g represents the time to exceed 2g and the height of the bar labeled 8g represents the time to exceed 8g, both of which are designed for the high-altitude mission previously discussed.

From figure 6 the limit load factor for the most suitable high-altitude interceptor may be selected. The airplane to select for the mission, therefore, would be the one which has the longest time to reach limit load factor but at the lowest practical limit load factor. In this hypothetical case, it would appear that an airplane with a limit load factor of 4g would be sufficient since it can be seen that little is gained in the time to reach the limit load factor by selecting a higher strength airplane. It might be added that if the percentage of flight time spent in the mission was as low as 1 percent or even 0.1 percent, approximately the same limit load factor would be selected for this case.

At this time it should be pointed out that these results do not indicate that every high-altitude interceptor should be a 4g airplane. The results shown here are a result of the particular conditions assumed for the simplified mission. The results obtained in other cases could be different from those shown here, depending on the radar ranges, speed ratios, and altitudes chosen.

If, on the other hand, the airplane were to be designed for both high- and low-altitude missions, the results could be considerably different. For example, the right side of figure 6 indicates the results for a case where 20 percent of the airplane flight time was spent in performing the high-altitude interception, 1 percent in a different low-altitude interception such as dive-bombing, and 79 percent in other operations. In this case, the high-altitude-mission probability curve, the low-altitude probability curve, and the standard curve are combined as before. It may be seen for this particular case that the low-altitude mission dictated the design limit load factor even though the airplane was assumed to be used in this mission only 1 percent of the time, and it is indicated that an 8g airplane would be selected as the airplane which would have a long time to reach limit load factor at the lowest practical limit load factor. Low-altitude missions would not always affect the results in this manner, however, for it is possible that the probability functions for some low-altitude missions might not involve the probability of high load factors, as was the case in this illustration.

Determination of Resultant Probability Curve

After selecting the limit load factor on this basis, the time-to-exceed curves for the mission are combined with the standard time-to-exceed curve for the airplane selected (in this case it would be a 4g airplane) to form the resultant curve, shown in figure 7. On the left side of the figure the probability curve for the high-altitude mission is shown with the standard curve for a 4g airplane. These curves are then combined according to the percentages of flight time spent in each activity to form the resultant curve which is shown on the right side of figure 7. The peak at the lower load factors is caused by gusts.

Although the possibilities of calculating probability curves for specific missions and the combination of these specific probability curves with more general curves to predict the overall load experience have been mentioned only in regard to positive symmetrical wing loads, there exists the possibility of extending the reasoning to other loads such as negative wing loads and horizontal- and vertical-tail loads, although more factors will enter into the problem and tend to complicate the situation.

Effect of Inadvertent Maneuvers on Loads

Although the tentative standard curve (fig. 4) appears to be adequate up to the limit load factor, it is not valid at load factors considerably greater than the limit, because inadvertent maneuvers may lead to much greater loads than could be obtained from a simple statistical extrapolation of data obtained at lower load factors. An indication of the effect of inadvertent maneuvers is shown in figure 8. The left-hand side of the figure indicates the frequency of occurrence of load-factor peaks for about 10,000 hours of fighter-type airplane operations. The solid line represents the ordinary distribution of load factors. For example, there are 10,000 load-factor peaks at 4g, about 1,000 peaks at 5g, and so forth. The inadvertency distributions are probably distributions such as those designated A or B which must be superimposed on the ordinary distribution. It may be noted that the ordinate is a logarithmic scale so that the magnitudes of the peaks of curves A and B are greatly magnified. These inadvertent load factors are caused by such things as airplanes trying to avoid obstacles, failures in control systems, and other emergency maneuvers. They may also be caused by airplane instability such as pitch-up or the more recently encountered lateral instability.

The probability or time-to-exceed curves based on these frequency distributions are shown on the right-hand side of figure 8. The solid curve represents the average flight time required to exceed a given load factor for the ordinary distribution and the dashed curves represent the values with the inadvertency distributions included.

In the past it is indicated that the inadvertency distributions were of the type indicated by the letter B. In other words, when an emergency or inadvertency occurred it usually resulted in a very large load and affected the results mostly at load factors greater than the limit load factor. Curves such as these have been obtained since World War II; however, the accuracy of these curves at high load factors is very poor, first, because of the very few points obtained in the number of hours of flight time usually available, and second because the records are rarely obtained from the airplanes which are destroyed because of the high loads obtained.

If, however, airplanes are to be flown operationally with such poor stability characteristics as have recently been encountered, an inadvertency distribution such as curve A might be obtained. In this case it is possible that the inadvertency distribution will affect the resultant distribution at lower load factors as well as high load factors such as indicated on the right side of figure 8. If this is the case, the tentative standard curve obtained from present operational airplanes would not be correct unless the inadvertency distribution could be added to it.

For example, if the type A inadvertency distribution were added to the high-altitude interception mission which was presented previously, a higher strength airplane would probably have to be selected instead of the 4g airplane, whereas the type B inadvertency distribution may not greatly affect the choice of the limit load factor. It would, of course, affect the shape of the resultant curve at high load factors.

CONCLUDING REMARKS

It is realized that in all the preceding discussion many questions still exist and will have to be dealt with by either analytical studies or the analysis of statistical data. For example, there are questions as to the validity and accuracy of the calculations of probability functions for a given mission. Such calculations could probably be made for many missions; however, for some missions, the probability function may require correlation with previous experience. One of the major questions concerns the determination of the percentage of flight time spent in performing each mission. This could be of importance if a large percentage of the flight time is spent in many specific missions.

Also there are questions concerning the use of a universal standard curve based on limit load factors for all the other airplane uses. It is believed that, on the basis of present knowledge, such a curve may be adequate up to the limit load factor. This curve, of course, will have to be revised gradually as the airplane characteristics change in future years. One of the important questions concerning this curve is the determination of the average number of load-factor peaks per hour. This number varies for different airplane types and uses and must be estimated from statistical data on past airplanes.

From the results of this study, the concept of stipulating the design loads on the basis of mission requirements appears to be feasible; however, statistical data will be needed in establishing the effect of missions on the load experience and the amount of time spent in each activity.

The work on this approach to the problem of design loads at the NACA is, as mentioned before, in a beginning stage, and the results that have been shown here have been presented to indicate a few of the possibilities of using statistical methods for correlation with design load requirements.

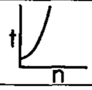
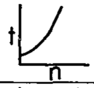
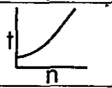
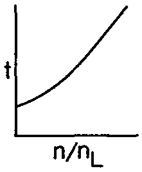
Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 22, 1955.

REFERENCES

1. Mayer, John P., Hamer, Harold A., and Huss, Carl R.: A Study of the Use of Controls and the Resulting Airplane Response During Service Training Operations of Four Jet Fighter Airplanes. NACA RM L53L28, 1954.

2. Mayer, John P., and Harris, Agnes E.: Analysis of V-G Records From Ten Types of Navy Airplanes in Squadron Operations During the Period 1949 to 1953. NACA RM L54G23, 1955.

TABLE I - AIRPLANE UTILIZATION

UTILIZATION OF AIRPLANE	FLIGHT MISSION	% OF TOTAL TIME	COMPONENT TIME-TO-EXCEED CURVES
COMBAT AND COMBAT TRAINING	HIGH-ALTITUDE INTERCEPTION	10	
	MED.-ALTITUDE INTERCEPTION	1	
	LOW-ALTITUDE INTERCEPTION	5	
	STRAFING	1/4	
	DIVE BOMBING	1/4	
	AIR PATROL, ETC.	12	
	OTHER MISSIONS	1/2	
PILOT FAMILIARIZATION AND SQUADRON OPERATIONAL TRAINING	CROSS COUNTRY (NAVIG.,FERRY, ETC.)	60	
	ACROBATICS	2	
	TAKE-OFF AND LANDING PRACTICE	5	
EQUIP. DEVELOP. DURING SQUAD. OPER.	TRIALS OF RADAR EQUIPMENT, ETC.	4	

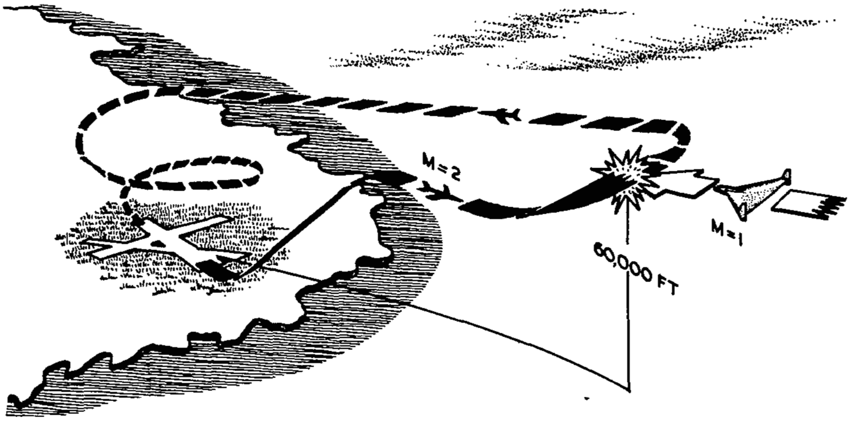


Figure 1.- Schematic drawing of high-altitude interception mission.

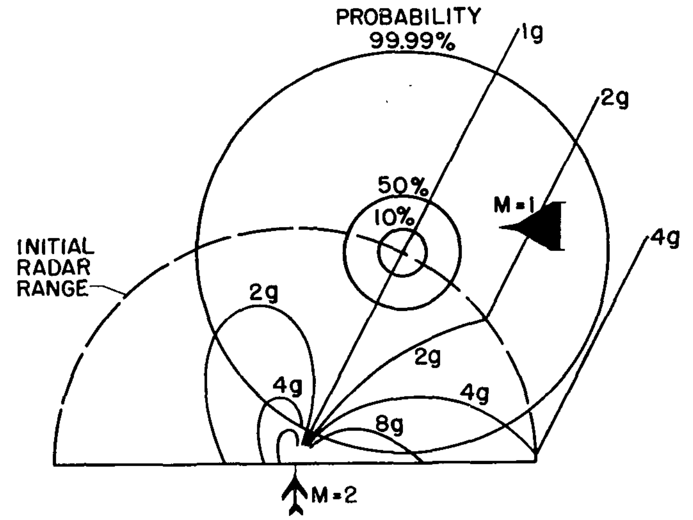


Figure 2.- Method of calculating probability curve for attack phase of high-altitude interception mission.

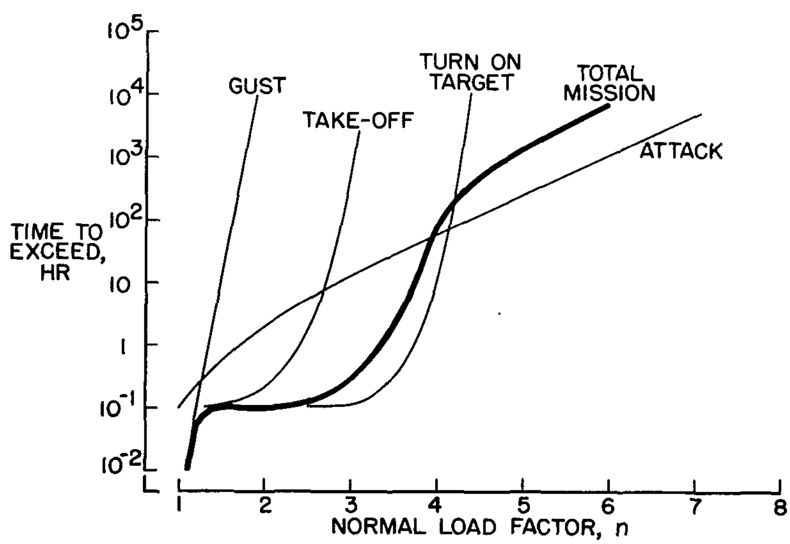


Figure 3.- Probability curves for various phases of high-altitude interception mission.

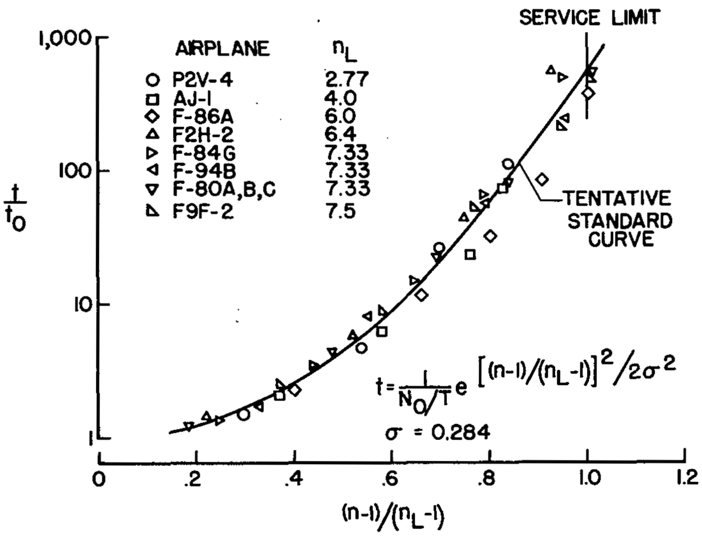


Figure 4.- Load experience for present operational airplanes.

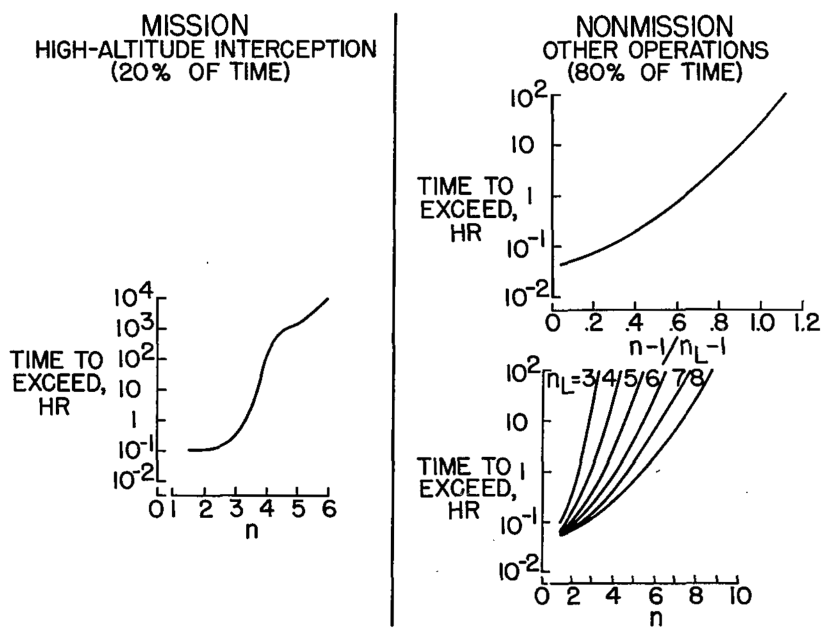


Figure 5.- Probability curves for high-altitude interception mission and nonmission operations.

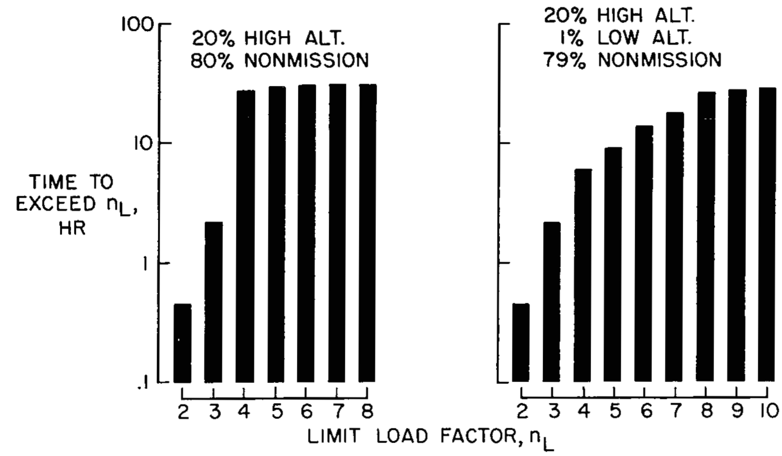


Figure 6.- Variation of time-to-exceed limit load factor with limit load factor.

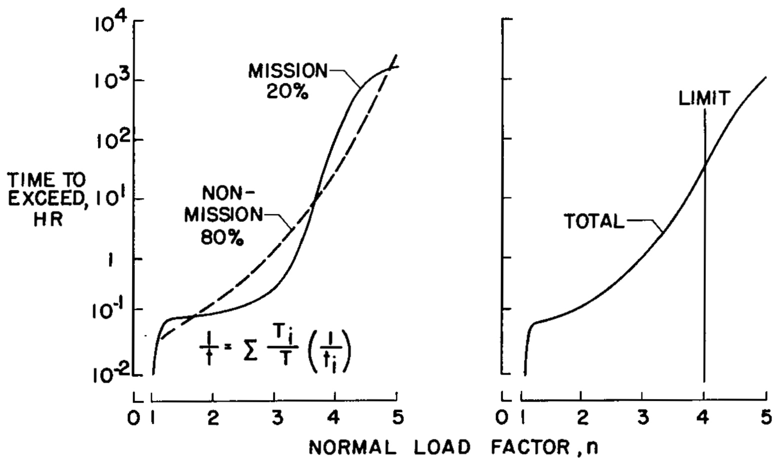


Figure 7.- Combination of mission and nonmission load-experience curves to form resultant load-experience curve.

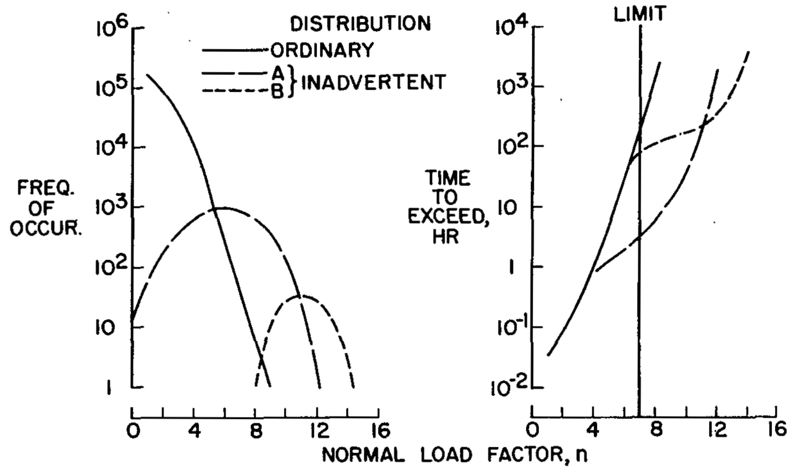


Figure 8.- Effect of inadvertent maneuvers on loads.

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